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SOLVING THE MULTIDIMENSIONAL MULTIPLE KNAPSACK PROBLEM WITH PACKING CONSTRAINTS USING TABU SEARCH

THESIS

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List of Variables

$a_{i,k}$ .... Amount of constraint k item i requires

b_k .... Amount of constraint k that has not been consumed

B_{volume} .... Volume the aircraft is capable of holding

B_{weight} .... Weight the aircraft is capable of holding

$B_{volume,j}$ .... Volume aircraft j is capable of holding

$B_{weight,j}$ .... Weight aircraft j is capable of holding

c_k .... Boolean: 1 if kth constraint is the tightest, 0 otherwise

FA .... Feasible after the item is added

FC .... Feasible currently, before the item is added

i .... Index used for items i={1,...,N}

j .... Index used for aircraft j={1,..,M}

k .... Index used for constraints k={1 (weight), 2 (volume)}

M .... Number of aircraft

N .... Number of items

PA .... Packable after the item is added

PC .... Packable currently, before the item is added

$\Pr_i$ .... Profit ratio for item i

$profit_i$ .... Profit associated with item i

$requirement_i$ .... Amount of resource k the item i requires, where $c_k = 1$

$s(x_i)$ ....Space item i occupies

S_{total} ....Total space available

$volume_i$ ....Volume required by item i

$weight_i$ ....Weight required by item i

x_i ....1 if item i has been selected, 0 otherwise

$x_{i,j}$ ....1 if item i has been selected for aircraft j, 0 otherwise

Abstract

This thesis presents a methodology for solving the military aircraft load-scheduling problems modeled as a multidimensional multiple knapsack problem with packing constraints. Because of the computational time associated with applying conventional algorithms to this class of problem, we employ the tabu search heuristic to determine how much cargo a heterogeneous group of aircraft can carry. This study extends the previous work of Chocolaad in two areas. First, we modify Chocolaad's algorithms to solve the multiple (rather than the single) knapsack problem under the constraints he defined for the Airlift Loading Problem. Second, we drop his assumption of a homogeneous group of aircraft. We validate our model by confirming its solutions with cargo loadmasters and comparing the performance of our algorithm with the benchmark program Win ALM.

Chapter 1 - Introduction

Captain Christopher Chocolaad provides a JAVA implementation of a tabu search heuristic to solve the geometric knapsack problem (GKP). His implementation employs two heuristics, each solving one basic aspect of the problem: knapsack and cutting stock. The knapsack problem is the class of problems requiring the selection of a group of items from a given set in a manner that maximizes their combined value, while conforming to the constraints of the knapsack. The cutting stock problem is the class of problems requiring the selection of a pattern that produces items of a required size out of the stock material, while minimizing waste or maximizing profit. Chocolaad's two heuristics work together by specializing in the enforcement of a portion of the constraints the load plan must conform to. Specifically, the knapsack heuristic selects the items to pack while enforcing weight and volume constraints. Periodically the packing heuristic is called upon to solve an expanded cutting stock problem, enforcing balance, axle weight restrictions, pounds per linear-foot limits, and hazardous cargo constraints. Because of the independent implementations of the knapsack and packing heuristics, a solution can be feasible with respect to the knapsack constraints (weight & volume), but infeasible with respect to the packing constraints (space conflicts, weight & balance, floor loading, & hazardous cargo) or vice versa. For clarity we restrict usage of the term *feasible* to describe a solution that conforms to the knapsack constraints and the term *packable* to describe a solution that complies with the packing constraints.

Chocolaad's research presents two limitations. Technically, it is a multidimensional single knapsack problem (MDKP) consisting of a single C-17, an assumption not valid under operational conditions. For example, it is quite likely several

aircraft, potentially of different types, must be packed at the same time. The Air Force's cargo fleet includes a wide array of aircraft such as the C-5, C-130, C-17 and KC-10, as well as the Civil Reserve Airlift Fleet (CRAF) available for crisis. Our implementation includes two types of aircraft: C-5 and C-17. Second, we present an extensive evaluation of Chocolaad's dual heuristic approach using current force planning data represented in files contained within Win ALM.

Anderson [2] describes the process the Department of Defense uses to develop and refine military deployment plans with the following 8-step process:

1) *Force Planning.* Identifying the forces needed to accomplish the mission and phase them into the theater of operations.
2) *Support Planning.* Identifying the amount and frequency of supplies, equipment, and personnel required for maintenance of the fighting forces.
3) *Chemical/Nuclear Planning.* Determining the possibility that these weapon types will be introduced in the conflict, and what impact they would have on operations.
4) *Transportation Planning.* Formulating a simulation of the transportation requirements and availablilities.
5) *Shortfall Identification.* Determining if the simulation produced in Step 4 will provide the needed supplies within the required time windows.
6) *Transportation Feasibility Analysis.* Determining if the transportation plan is not only feasible but also has slackness built in, so that there is some flexibility within the load plans.
7) *Time-Phased Force and Deployment Data* (TPFDD) *Refinement.* Assigning actual units to fill cargo positions within the deployment.

8) *Documentation.* The final written product, ready for future reference.

Steps 4 through 7 make up the iterative process depicted in Figure 1 (from Figure 6-19 in Anderson [2]). This research addresses the question asked in Step 4: Can the enumerated fleet of aircraft move the listed cargo? Since each aircraft can be modeled as a knapsack with multiple constraints, packing a fleet of planes is a multidimensional multiple knapsack problem (MMDKP). This restricted loading or knapsack problem is important to consider, because unless it is solved, the 8-step process can not be completed. Without the 8-step process in place, deployments must be generated during times of crisis rather than from a previously generated plan. Furthermore, the problem's size is very large: the number of items listed within a TPFDD approaches 81,000 items. Problems with cargo lists of this size cannot be solved quickly, thus delaying the deployment and allowing the crisis to escalate.

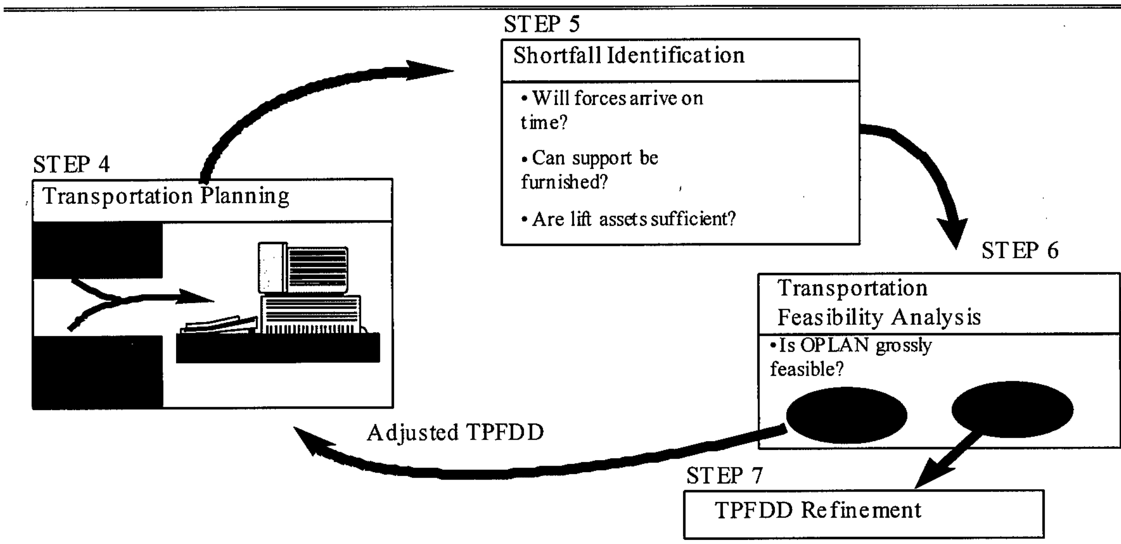


Figure 1. Transportation Planning

We present our results in the following manner. Chapter 2 describes the Airlift Loading Problem (ALP) and associated literature, as well as algorithms for solving the ALP. Chapter 3 describes our approach for solving the MMDKP. Chapter 4 presents of our results and the validation our packing algorithm. Chapter 5 concludes with suggested future extensions of this research.

Chapter 2 - Problem Description and Literature Review

The general knapsack and cutting stock problems bound the complexity of the airlift-loading model. Both problems are categorized as NP-complete (i.e., their computational growth rate does not have a polynomial bound) and have thus attracted a large amount of attention. The packing problem has also received considerable attention because of its importance within industry. Surveys reflect the fact that most of the work done on packing problems has concentrated on problems with few dimensions and regular shaped objects [10,17,14]. These surveys also comment on the fact that the few works that deal with three-dimensional packing problems make use of ad-hoc rules, leaving none distinctly superior to the others. Szykman and Cagan [39] extend a simulated annealing approach to the three-dimensional packing problem to solve the two dimensional VLSI layout technology. Their implementation enforces the separation restrictions needed for the ALP and achieves high packing density. Chocolaad's packing heuristic differs in that it is required to enforce the balance load restriction demanded in ALP, and his implementation utilizes reactive tabu search.

The general knapsack problem [12] deals with only one constraint, and can be formally described as: (All variables are listed on pages vii and viii.)

$$\text{Maximize} \quad \sum_{i=1}^{N} profit_i * x_i$$

$$\text{Subject to} \quad \sum_{i=1}^{N} weight_i * x_i \leq B_{weight} \qquad (1)$$

$$x_i \in \{0,1\}$$

This problem has been shown to be NP-hard [35]. Most realistic problems require meeting several constraints simultaneously and are thus designated multidimensional [21]. In addition to (1), our application requires complying with the volume constraint

$$\sum_{i=1}^{N} volume_i * x_i \le B_{volume} .$$

When more than one knapsack is packed at once the problem becomes a multiple knapsack problem [18] and is formulated as:

$$\text{Maximize} \quad \sum_{j=1}^{M}\sum_{i=1}^{N} profit_i * x_{i,j} \tag{2}$$

$$\text{Subject to} \quad \sum_{i=1}^{N} weight_i * x_{i,j} \le B_{weight,j} \qquad \mathrm{j} \in \{1,..,M\}$$

$$\sum_{i=1}^{N} volume_i * x_{i,j} \le B_{volume,j} \qquad \mathrm{j} \in \{1,..,M\}$$

$$\sum_{\mathrm{j}=1}^{\mathrm{M}} x_{i,j} \le 1 \qquad \mathrm{i} \in \{1,..,\mathrm{N}\}$$

$$x_{i,j} \in \{0,1\}$$

The packing problem can be solved as a two dimensional cutting stock problem with floor space as the stock material. The cutting stock problem requires selecting a pattern that produces items of a required size out of the stock material, while minimizing waste or maximizing profit [14] and can be formulated as:

$$\text{Maximize} \quad \sum_{i=1}^{N} profit_i * x_i$$

$$\text{Subject to} \quad s(x_\alpha) \cap s(x_\beta) \equiv \phi \qquad \forall \alpha \ne \beta \text{ where } \alpha, \beta \in I = \{1,..,\mathrm{N}\} \tag{3}$$

$$s(x_i) \subseteq S_{total} \qquad \forall \mathrm{i} \in \{1,..,\mathrm{N}\} \tag{4}$$

$$x_i \in \{0,1\}$$

Equation (3) reflects the requirement that no two items occupy the same space, no overlap, while (4) enforces the requirement that all items be placed within the allotted area, no protrusion. As each item is loaded, that portion of the floor space is essentially cut away. The literature employs two strategies to solve problems of this type: *fill gap* and *top down* [11,44]. Both begin by sorting the items to be packed based upon a descending order of priority. The *fill gap* method first identifies and then fills a space or section with the first item on the list. Conversely *top down* selects an item then finds the smallest hole that it can fit in. Other heuristics in the literature differ from the above mainly in their sorting priority. Cutting stock algorithms are most effective when a pattern can be found once and then reused to cut large numbers of the same subset of items.

Specialized algorithms have been developed for solving the packing problem when the items are not of similar shape. Heidelberg [27] discusses several algorithms that build levels of items. Each employs a timing strategy for sorting the items before placing them on the aircraft. Heidelberg also develops his own algorithm, capable of finding solutions superior to those found using the other algorithms he discusses; however, it is computationally expensive. The efficiency of Heidelberg's algorithm derives from eliminating several side-constraints, the most important being that the bin can be divided only by levels made of straight lines. The alternative approach allows the barrier between the packed items and the unused space to consist of up to three different levels. In so doing, gaps that would otherwise have gone to waste can be filled.

The airlift-loading problem is a complex extension of both problems. The cutting stock satisfies the geometric constraints of no overlapping cargo as well as boundary constraints, while the knapsack imposes the volume and weight restrictions. However, a realistic solution must conform to additional constraints that depend on the specifications of the aircraft; i.e., the need for balance, axle weight restrictions, pounds per linear-foot limits, and hazardous cargo restrictions.

The most difficult aspect of the problem is satisfying the constraints that must be added to the cutting stock problem. Manual load planning typically solves the cutting stock portion by utilizing a scaled layout of the plane and the cargo to be loaded [11]. Once a layout efficiently utilizes the floor space, the constraints reflecting the specifications of the plane must be checked (surrogate constraints can sometimes speed up this tedious procedure). The violation of any single constraint requires adjusting the load and repeating the process until both a feasible and packable (but not necessarily optimal) load plan is found.

Because of the tedious and time consuming nature of the problem, Huebner advocates implementing a computerized method that plans cargo loads and layouts, while streamlining the enforcement of constraints [28]. One of the first significant implementations of this approach is Deployable Mobility Execution System (DMES), which utilizes a modified cutting stock heuristic to generate useable cargo loads [11]. The usefulness of such an approach was demonstrated when DMES saved $2.5 million in its first full-scale utilization during the Grenada rescue operation in 1983. DMES implements a cutting stock heuristic based on a "fill gap" algorithm developed by Eilon and Christofides [18]. DMES was restructured in 1985 to the Computer Aided Load

Manifesting (CALM) program and is used throughout the USAF as a standard. These software packages can not be effectively employed to solve a large scale ALP. Yost and Hare discuss a method to estimate solutions for large scale ALP by generating both an upper and lower bound [44].

The current software package used by the Air Force to solve the ALP is Win ALM, primarily used by the Air Force Studies and Analyses Agency (AFSAA). AFSAA uses Win ALM to determine the number of sorties needed to move a given amount of cargo, as well as the portion of cargo that a given fleet can move. Win ALM has received upgrades over the years; however, the main loading algorithm has not changed.

Theodoracatos and Grimsley [40] show that since the packing problem is NP-complete, a meta-heuristic should be employed. Chocolaad follows this advice and utilizes the heuristic tabu search as his underlying method. Tabu search is a technique developed in the 1970's; however, it did not take on its current form until 1986. The technique implements a systematic use of memory by maintaining not only the current solution, but also information on the search path used to reach it. Tabu search describes the *search space* as a set of solutions and the moves required to traverse them. Each *solution node* has the attributes of value, usability, and tabu status (tabu active or tabu not active). The *neighborhood* of a solution is the set of all solutions exactly one move away. (For our work, a move is the selection of an unpacked item or the unpacking of a selected item.) This neighborhood is then adjusted by restricting the movement to tabu active solutions for a tabu tenure, when the tabu status of a solution is reset to tabu not active. Tabu statuses are not rigidly enforced; they can be overridden by special conditions

called aspiration criteria. The search history it maintains enables tabu search to force the search out of local minimums and to prevent cycling [22].

The promising results produced in the works by Dowsland [15] and Glover [25] in the area of simple tabu thresholding (STT) prompted Chocolaad's use of this technique for his packing heuristic. Chocolaad's STT consists of two alternating phases: *Improving* (Figure 2 [9]) advances the solution towards an optimum, and *Mixing* (Figure 3 [9]) forces the searching out of local optimum. These two phases encompass an important aspect of Tabu Search, intensification and diversification. The *Improving* phase concentrates the search, by only allowing moves of small distances and requiring them to find solutions of higher quality. The *Mixing* phase diversifies the search by accepting moves without regard to their value, and by allowing larger moves.

```
Improving Phase
  While Not at Local Optimum do
    Apply Candidate List Strategy by a Block Random Order Scan
    if move is improving then
      accept move
    end if
  end while
```

Figure 2. Pseudo Code for Improving Phase

```
Mixing Phase
  Select a tabu timing parameter T
    for I=0, I<T do
      Apply Candidate List by a Full Random Order Scan
      automatically accept move
    end for
```

Figure 3. Pseudo Code for Mixing Phase

The knapsack heuristic used within Chocolaad's study (Figure 6) is based on a combination of Glover and Kochenberger's [26] critical event tabu search strategy and the reactive scheme developed by Battiti and Tecchiolli [6]. Critical event tabu is used to

search the solution space in the area that surrounds the border between feasible and infeasible solutions. A *constructive* phase (Figure 4 [9]) adds items to the knapsack even after the solution is infeasible, while a *destructive* phase (Figure 5 [9]) forces the solution back to feasibility by removing items. A reactive scheme determines how many moves the constructive phase is allowed to take into infeasible space before the destructive phase takes over, and it also determines how far into feasible space the destructive phase may move without returning control to the constructive phase. Critical event tabu gets its name from the occurrences of "critical events." In our case such events occur in two cases: when either the packing or knapsack constraints are violated, and when both have been restored.

Constructive Phase
  While feasible = true **do**
    if no component x_i of X can be increased from 0 to 1 except by violating feasibility **then**
      if cx > cx* **then**
        x* ⇐ x
      end if
      feasible ⇐ false
    else
      choose an x_i to increase from 0 to 1 such that the move maintains feasibility
    end if
  end While
  while feasible = false **do**
    countSpan ⇐ countSpan + 1
    if countSpan > span or all x_i=1 **then**
      return
    else
      choose an x_i to increase form 0 to 1
    end if
  end while

Figure 4. Pseudo Code for Constructive Phase

Destructive Phase

```
countSpan ⇐ 0
While feasible = false do
   Select an x_i to change form 1 to 0
   if solution is feasible then
      if cx > cx* then
         x* ⇐ x
      end if
      feasible ⇐ true
   end if
end While
while feasible = true do
   countSpan ⇐ countSpan + 1
   if countSpan > span or all x_i =0 then
      return
   else
      choose an x_i to decrease form 1 to 0
   end if
end while
```

Figure 5. Pseudo Code for Destructive Phase

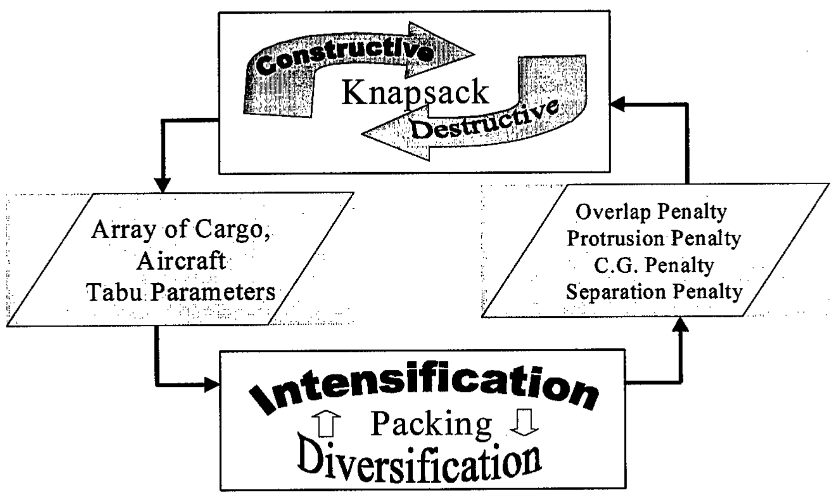


Figure 6. Chocolaad's Implementation

Chapter 3 - Implementation

Our study maintains Chocolaad's packing heuristic, and modifies his knapsack heuristic to improve its performance. One weakness of Chocolaad's approach is that it models a single, rather than multiple, knapsack. In order to alleviate this drawback we implement a heuristic that extends Chocolaad's approach by adding another function to the constructive phase that selects the best aircraft for a given item. The best aircraft for a given item is the one that directs the search path towards optimizing equation (2). This decision is central to the knapsack heuristic of our implementation. Items are prioritized for packing and removal using the same method used by Chocolaad, which uses the total weight of a load plan as a means of scoring it. *Therefore, for our implementation, the profit of an item is set equal to its weight.* We continue using this method of determining the value of each cargo item so direct comparisons can be made.

Our constructive phase selects the next item to be packed by searching the unselected items for the item with the largest profit ratio (*Pr*). In a real world implementation the utility (not just value but also importance) of an item may be affected not only by a "value," but also by a due date, or even the nature of other items already loaded. In our implementation only its weight is used to define an item's profit value. (i.e., $profit_i = weight_i$)

$$Pr_i = {profit_i}/{requirement_i} \tag{5}$$

Where

$$requirement_i = \sum_{k=1}^{2} c_k * a_{i,k} \tag{6}$$

$$c_k = \begin{cases} 1 & \text{If } b_k = b_{min}\ \forall k \in constraints \\ 0 & Otherwise \end{cases} \tag{7}$$

The profit ratio is a ratio between the item's profit and its requirement from the one constraint that is given emphasis by (6) and (7). The selection of constraints is not done based on the percentage of unused constraint capacity (b_k/B_k) but on the numerical value of how much is left. Thus as an example consider a knapsack that has two constraints, one with a very large numerical value and the other is relatively very small. In a situation where most of constraint one has been utilized, while constraint two has not been consumed, it is still possible for constraint two to receive emphasis. During the first half of the constructive phase, the tabu statuses are used as a penalty in conjunction with the profit ratio (5) in order to direct the search. Our implementation maintains two variables used in these tabu penalty functions, *tabu frequency* and *tabu recency*. During the second half of the constructive phase (after the solution is infeasible), only the profit ratio (5) is considered. In a similar manner, items with the smallest profit are the first to be selected for removal by the destructive phase. During the first half of the destructive phase tabu statuses are used along with the profit ratio. Once the solution becomes feasible again the only selection criteria is the profit ratio (5).

Having selected the next item to be loaded, the next decision is which aircraft to load the item on. In other words, given the current load plans and the item to be loaded, to which aircraft's manifest should the item be added. This question is solved in our implementation by an aircraft selection method. This method solves the question in two parts; first the aircraft are prioritized using their feasible and packable status, then the best

subset of aircraft are prioritized using the requirements of the items and remaining available aircraft weight and volume resources.

Aircraft that are currently packable and feasible are given priority over those that are not. Likewise, aircraft that will remain packable and feasible after the item is loaded are given priority over those that will not. If a load plan can only comply with one set of constraints, feasibility is given preference over packablity. Each aircraft is grouped into one of eight sets using the logic tree in Figure 7. As an example, an aircraft is currently feasible but not currently packable. It will therefore fail the first test and then checked for current feasibility. Because it is feasible, the logic structure determines that it failed the first test because of its packable status, and it proceeds to test for feasibility after the item is added. If the aircraft will remain feasible then it is part of set 4: otherwise it is part of set 5. The logic structure depicted in Figure 7 gives preference to aircraft in the set with the smallest index.

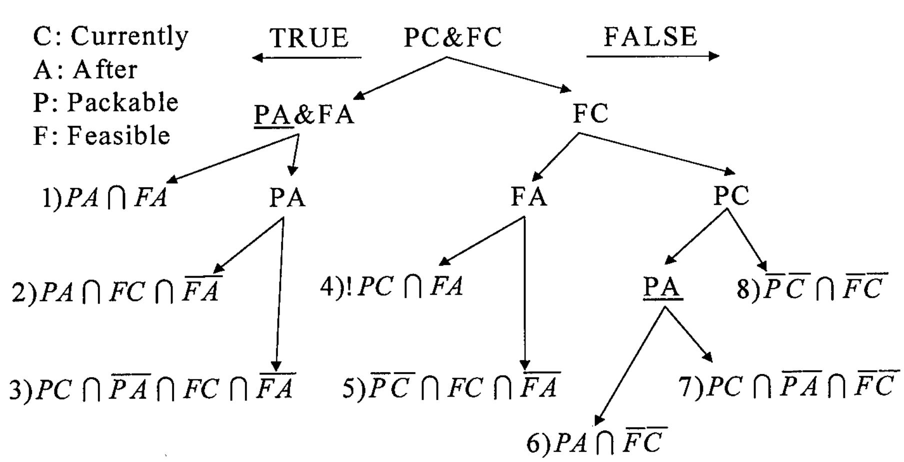


Figure 7. Logic Structure for Selecting the Best Aircraft

The second part of our decision process is very much like that of the MMDPK. Khuri, Bäck, and Heitkõtter [31] look at a similar problem using genetic algorithms; however due to the nature of that heuristic, their work provides no decision criteria. Our objective is to consume the resources in an even manner and thus minimize the amount of unused aircraft capability without knowing anything about the correlation between the constraints (see Appendix D for a simple notional example). With this objective in mind, our method uses the requirements of the selected item and the amount of unused capacity of the aircraft in the selection process. The selection function determines the proportions of the unused aircraft capability as represented by the slackness in each constraint and the requirements of the item (already selected).

$$P_{j,k} = {}^{a_{i,k}}\!/_{b_{j,k}} \quad \forall\ k \in \text{Constraint, and } j \in M \tag{8}$$

$$dif_j = P_{j,\max} - P_{j,\min} \quad \text{For all } j \in M \tag{9}$$

Specifically, the aircraft with the smallest dif will receive the item.

We verify this approach by emphasizing the second stage decision represented by (8) and (9) by relaxing the packing constraints. By simplifying the first stage decision of selecting the aircraft the logic tree reduces to the one shown in Figure 8.

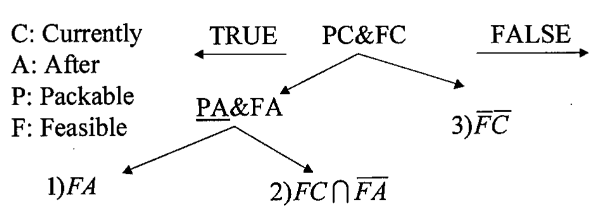


Figure 8. Simplified Decision Tree

Figure 9 presents the effectiveness as a function by measuring the weight carried by the aircraft. Because a heterogeneous aircraft set is used solution qualities are measured by the total weight of the load plan divided by the capacity (weight) for the aircraft. The problems solved were generated using the flat files within Win ALM. There are ten Unit Groups listed within the sample study, each containing personnel, their equipment, and cargo items. The concern of this study is strictly oriented towards cargo items and as such only unit groups 3 through 8 were used. Figure 9 and Table 1 were generated by solving each of these six problems ten times. Statistically speaking the solutions are in two sets. The one and two aircraft problems are not statistically different from each other, but are different from all of the rest. Problems three through seven are not statistically different from each other, but are statistically different from one and two. (The Large-Sample α-Level Hypothesis Test is used to determine the statistical difference between the means throughout this paper, with an α-Level of 0.10.)

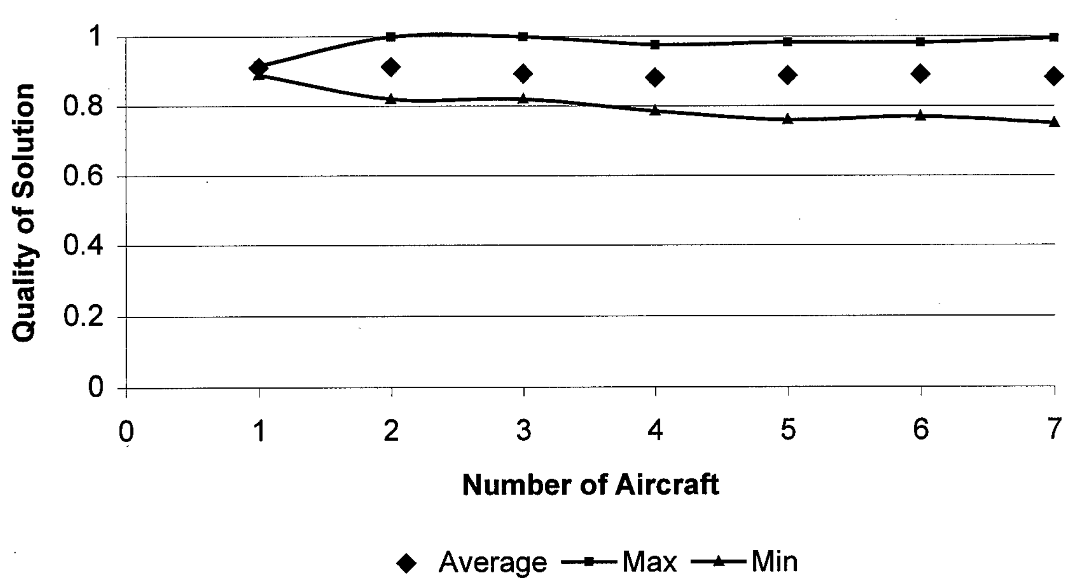


Figure 9. Proportion Function's Consistency

Table 1. Proportion Function

	1	2	3	4	5	6	7
Average	109372.5	109289.7	107187.7	105823.6	106541.9	106926.2	106058.9
Standard Deviation	577.18	3784.12	4907.76	5227.89	6077.39	5705.53	6224.72
Max	109993	119882	119846.3	117104	117939	117800	119360
Min	106834	98375	98375	94170	91178	92323	89964

Another modification to Chocolaad's algorithm addresses the aspiration criteria and the computational growth generated by increasing the number of aircraft. Chocolaad implements very simple aspiration criteria – each time a critical event occurs he looks for an item to add to the selected list while maintaining the load plan's feasible and packable statuses. His aspiration criteria do not consider an item's value or tabu status. Computationally, this is expensive because the packing algorithm checks the load *each* time an item satisfies the knapsack constraints. The search continues until either an item is found that can be packed or the list of items is exhausted. If such aspiration were maintained for a multiple aircraft problem, a similar search would need to be conducted for *each* aircraft at *each* critical event. This would make the aspiration even more computationally costly, and ultimately unmanageable, even for small fleet sizes.

We first investigate the impact of eliminating the aspiration criteria while increasing the number of cycles through the critical event tabu from 300 to 600. Problems generated from the Win ALM flat files are each solved ten times to demonstrate the computational time required. The computational results of Chocolaad's original code, using a single C-17, produces an average load of 91,648 Lbs. and require on average 183 seconds of computational time. (All computations were preformed on a Dell Latitude, PII 266.) Solutions based on the absence of aspiration criteria improve by an average of 8.59% while the computational time decreases by 92% to 15 seconds. Both of these

differences are statistically significant. Table 2, Figure 10, and Figure 11 depict the distributions of the different implementations.

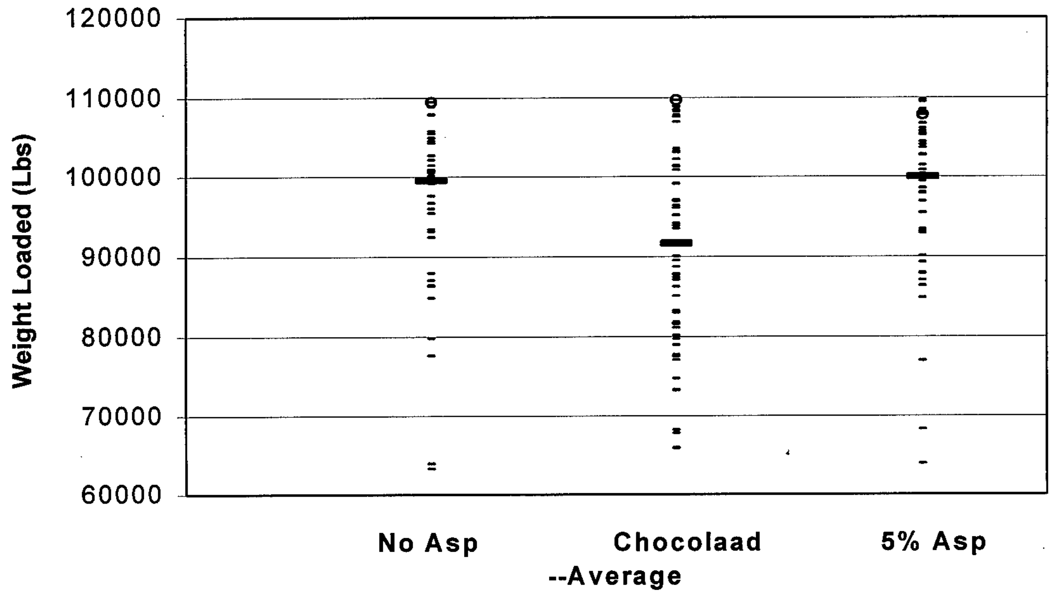


Figure 10. Weight Loaded on a Single C-17

In spite of this improvement in the quality of the solution, we are uncomfortable ignoring the effective tabu search implementations found in the literature that use aspiration criteria to overrule tabu status. Therefore we reinstate Chocolaad's aspiration criteria with a modification that limits the aspiration search to 5% of the items. Additionally, the starting point of the search was changed from Chocolaad's technique that begins with the tail end of the item list to a random selection that assigns equal probability of selection to each item. On average, these solutions are a statistically significant 9.1% better than Chocolaad's, while finding solutions in 11% of the time (a statistically significant decrease in computational time). Furthermore, the results from the random aspiration implementation improve on average by 0.5% over the no-aspiration results and require 24% longer computational time. There is no statistical difference

between the solution quality of the no-aspiration implementation and those produced by the 5% aspiration technique. The run times for the 0.5% and no-aspiration are also not statistically different. Even though this insignificant improvement comes at the cost of computational time, we maintain this 5% strategy.

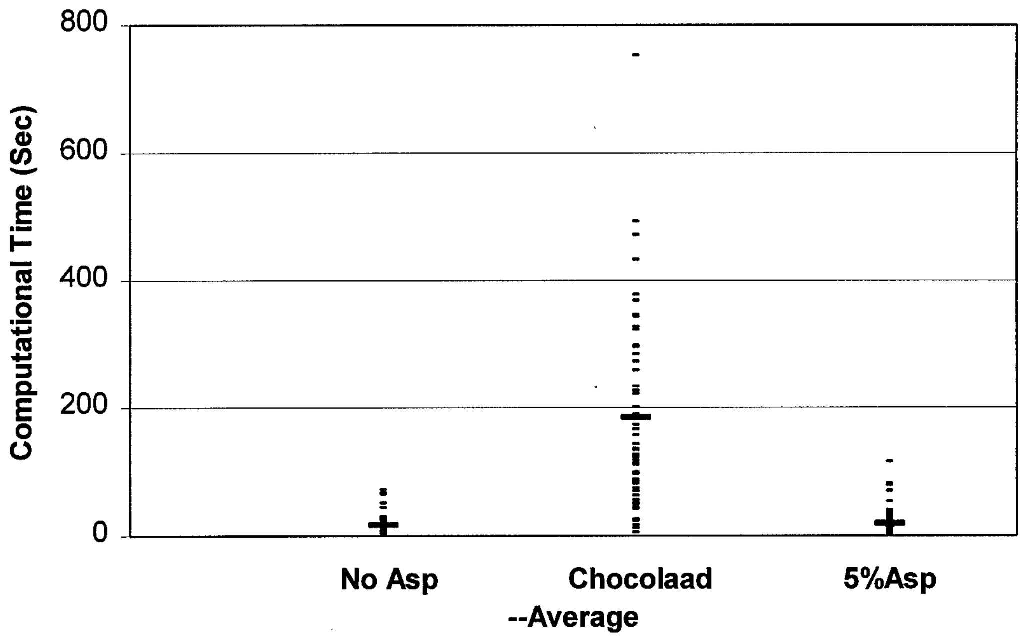


Figure 11. Computational Time for a Single C-17

Table 2. Single C-17

	No Aspiration	Chocolaad	5% Aspiration
Time (Seconds)			
Average	15.162	183.446	18.843
Standard Deviation	15.439	150.822	21.919
Max	70.310	752.540	114.020
Min	1.590	4.340	1.590
Score (Total weight Moved, Lbs)			
Average	99496.7	91648.2	99984.9
Standard Deviation	10696.6	12765.3	10182.8
Max	109500	109700	109750
Min	63290	65909	63925

Chapter 4 - Results and Validation

In order to understand and utilize the performance of Chocolaad's knapsack and packing heuristics, we investigate three ways to combine them. The differences are based on how many aircraft may be packed simultaneously and the conditions under which an aircraft can be considered packed and sealed. Sealed defines the state of an aircraft when a solution has been found and no further effort will be spent in finding a better one. These different mixes are summarized in Table 3.

Table 3. Mixing Strategies

Name	Knapsack Strategy	Packing Strategy
Sequential	Sequential	Individual
All/All	All at Once	All at Once
All/One	All at Once	Individual

The *Sequential* method is essentially the same approach Chocolaad uses. The aircraft are packed sequentially, with each plane cycled through the knapsack and packing heuristics individually. The next plane in the fleet is activated only upon sealing the previous plane. The two main strengths of this method are (i) speed, because the item list is modeled as being accessed by one loadmaster at a time; and, (ii) the requirement of having more than one load be packable at a time is relaxed.

The *All/All* mix initializes the entire fleet at the beginning, and requires all aircraft to be feasible and packable at the same time. Alternatively, the *All/One* mix requires only one plane to be feasible and packable at a time. This one difference is represented in the criteria for a critical event. *All/All* critical events occur in two cases: (i) when the *first* aircraft becomes either unpackable or infeasible; and, (ii) when the *last* aircraft becomes

both feasible and packable. *All/One* critical events occur when *any* aircraft meets either of the *All/All* critical events. The two mixes also differ in the driving force behind their computational growth. *All/All* cycles a predetermined number of times between constructive and destructive phases (regardless of the number of aircraft). As such, the driving forces behind its computational growth are the two methods that consume the majority of its run time, aspiration criteria and the aircraft selection method. Conversely, *All/One* has a predetermined number of cycles between each time an aircraft is sealed; thus, the total number of cycles between constructive and destructive phases depends on the number of aircraft. As the number of aircraft increases the number of cycles become the most dominant factor of the growth rate.

Table 4, and Figures 12 and 13, present the computational results of our three implementations. Air Force bases have ground capacities ranging from one to ten. Since the loadmasters will only be working on a section of these at a time we restrict the fleet size for our implementations to no more than five.

Table 4. Computational Results

Number of	Sequential		All/All		All/One	
Aircraft	%	Time	%	Time	%	Time
1	59.4	12.2	60.7	3.5	69.8	28.9
2	59.5	17.7	53.5	79.0	69.9	92.0
3	61.6	31.2	51.9	146.6	69.6	212.9
4	62.1	54.6	46.0	206.9	72.4	493.4
5	61.4	73.9	42.6	310.3	72.9	994.5

As mentioned before, the solutions are scored by the load's total weight. As such, the quality of the solution can be measured by the percentage of the aircraft weight capacity that was used by the load. Because of the large number of items in each of the

problem sets, the sequential implementation maintains consistent solution quality and linear growth in computational time as the number of aircraft is increased. This linear growth is caused by the consistent computational cost of the aspiration criteria. The other costly method, deciding between active aircraft, is not a factor since only one aircraft is active at a time.

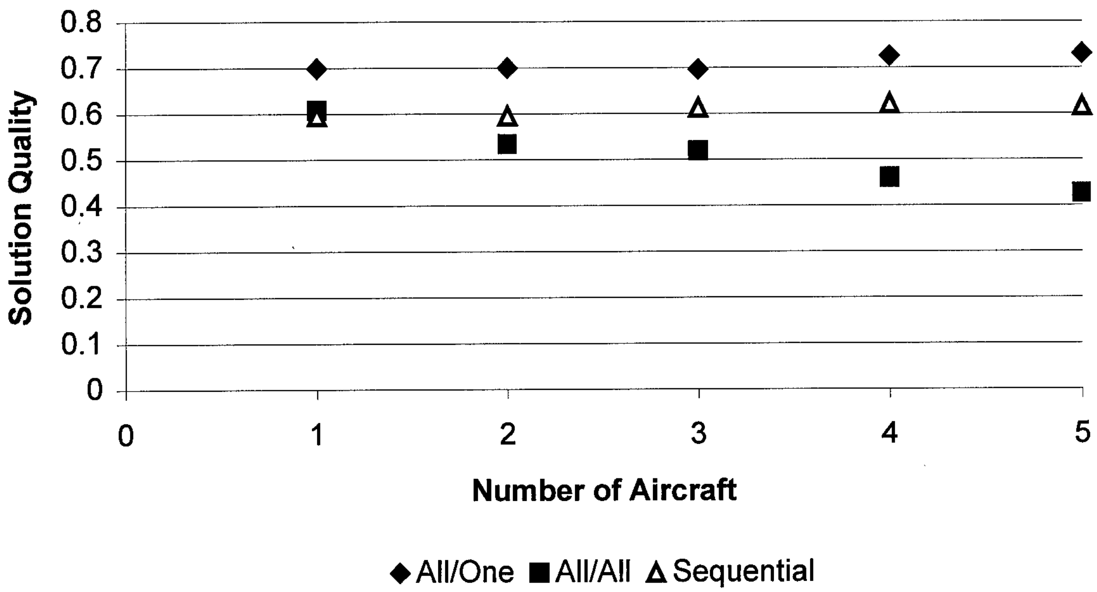


Figure 12. Solution Quality

All/All's solution quality gets progressively worse as fleet size increases. This degrading solution quality can be attributed to the constraint that requires all of the aircraft to be both packable and feasible at the same time, with a main contributing factor to this pattern being the critical events. As fleet size increases, the number of critical events per aircraft decreases, and with it, the solution quality. The growth in computational time for this strategy is related to the cost of the aspiration criteria. Because the computational time required per aspiration increases so much, the growth rate of the method is linear even though the number of critical events decreases.

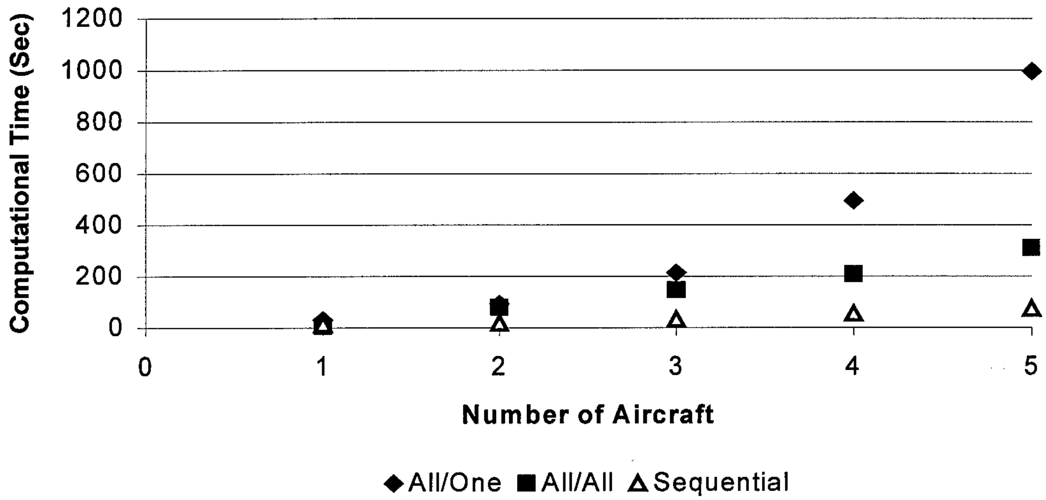


Figure 13. Computational Time

When the constraint is relaxed, as in *All/One*, the solution quality surpasses those of the *Sequential* method. The increase in solution quality *All/One* has over *Sequential* can, in part, be credited to the increased number of cycles spent doing the search since the tabu statuses are able to force the search away from more of the local optimums. Relaxing the constraint requiring multiple aircraft to be simultaneously packable and feasible generates the positive slope of the solution relative to the number of aircraft. Another reason why *All/One's* solutions are of high quality is the manner and conditions for a critical event. Critical events occur *each* time an aircraft enters or leaves the status of being *both* feasible *and* packable. Not only does this generate a larger number of critical events, but it also makes it possible to save the best individual feasible and packable solution found in each set of cycles.

As previously mentioned, the main contributor to the growth rate in computational time is the increased number of cycles with large fleets. Figure 14 represents the incremental difference in computational time the last aircraft causes. This

incremental difference is found by the difference between the run time for *All/One* with *M* aircraft and then again with *M-1* aircraft. The growth rate of this incremental difference is only slightly greater than that of *All/All.* This is further evidence that the increased number of critical events contributes to the growth rate, but with considerably less impact than the number of cycles.

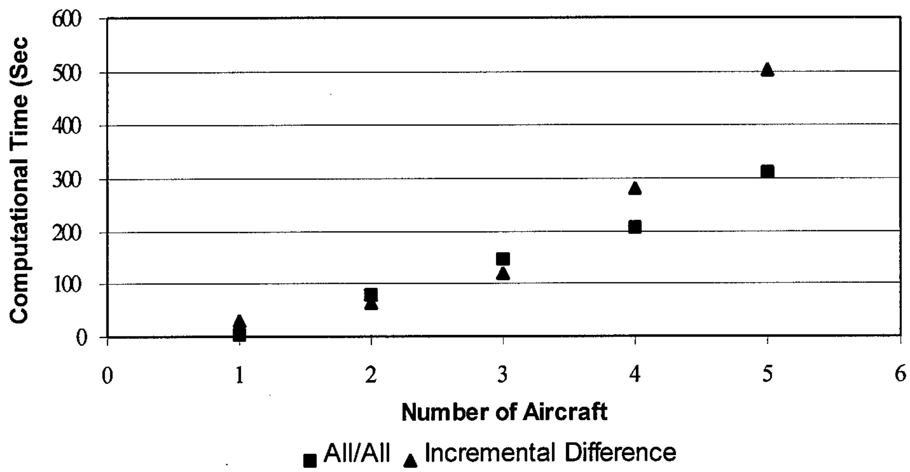


Figure 14. *All/All* and Marginal Increase of *All/One*

We conclude from the data that if computational time is important, the *Sequential* is the best method to use. It has virtually no growth rate and maintains consistency in solutions. On the other hand, *All/One* finds superior solutions to those of *Sequential;* if computational time is not important, we would recommend this method.

A second focus of this thesis is to validate the packing heuristic. The approach for this phase was to generate 19 load plans from the dual tabu heuristic and 30 load plans from Win ALM for a C17 loadmaster[1] to evaluate their operational feasibility. Air Force

[1] SMSgt Patrick R. Farley from the C-17 System Program Office. SMSgt Farley has 17 years of experience as a loadmaster, with approximately 5600 flight hours.

loadmasters are enlisted personnel responsible for packing and securing cargo loads. The combined 49 load plans were presented to the loadmaster in a format without reference to the generating algorithm. Consequently, in his evaluation the loadmaster could not distinguish which algorithm had generated any particular load. A summary of the results is presented in Table 5, while full details can be found in Appendix B.

The 19 load plans using our tabu heuristic were generated using the *All/All* strategy. Two problems were selected and solved four times each using a complement of four C-17s in an effort to generate load plans that were distinct. Unfortunately, only 19 of the 32 load plans generated were different; thus these 19 load plans were submitted to the loadmaster for validation. With one exception, all 19 plans were deemed operationally functional. The one load plan that failed validation did so by only a small margin in lateral space related to the ramp encroachment. Specifically the packing algorithm divides the aircraft in different sections to account for heterogeneous floor tolerances and balance calculations. However, it does not account for the 10-degree up angle the ramp has relative to the main floor during flight. Finally, in general, the loadmaster concluded that all of the load plans had tolerable side to side spacing and usually 20″ of lateral space free, a key difference between our packing algorithm and the older benchmark Win ALM.

The Win ALM-based solutions are derived from two problems, similar to those used by our heuristic. Each Win ALM problem had a complement of 15 C-17s and differs in that not only cargo items but also personnel and their personal equipment (pax) are modeled. Of the 30 Win ALM load plans generated for validation, 11 failed (details

in Appendix C). Furthermore, the loadmaster commented that seven of the 19 passing loads might fail due to a potential lack of space for tie downs. Finally, Win ALM does not account for the fact that any item exceeding 65,000 Lbs must be center loaded, a key contributing factor to several rejected load plans.

The impact of these faulty solutions on the operational use of this software package can be significant. If Win ALM were used within the 8-Step process outlined in Chapter 1, it would underestimate the aircraft requirements and thus make the result unusable. When used in an operational environment the likelihood of operationally unusable load plans dictates that each load be carefully inspected. The purpose of the software is to save time, thus the required inspections make the implementation less effective. The software's effectiveness is further hindered by invalid load plans because as they are found, the problem must be either resolved or the invalid loads must be adjusted. If the load is adjusted the excess cargo must be placed back in to the database of unpacked cargo.

Win ALM suggests solutions that average 91.1%, higher than the 87.9% generated by this study; however this difference is not statistically significant. When only feasible loads are compared, the average Win ALM result drops to 88.9% while ours remains at 87.7%, once again not statistically significant. Win ALM's average drops further when the conditional load plans are discarded, to an average of 87.3%.

Run times from Win ALM are not included because the software package does not provide a method for measuring computational times, and it was not possible to add such a capability. Manual measurements of solution times are impractical because Win ALM solves its fleets in a manner similar to the *Sequential* method used in this research.

Win ALM's implementation is very fast, and the human error generated during manual timings make such results unusable.

Table 5. Validation Results

Chalk[2] Number	Win ALM			Romaine/Chocolaad		
	# of Items	%Capacity	Validation	# of Items	%Capacity	Validation
1	8	82.1	**Conditional**	1	98.0	Yes
2	8	82.1	**Conditional**	2	79.8	Yes
3	9	82.3	**Conditional**	2	81.6	Yes
4	9	87.3	**No**	2	75.4	Yes
5	9	91	**No**	3	91	Yes
6	8	94.4	**No**	4	96.5	Yes
7	9	97.1	**No**	2	88.7	Yes
8	9	99.6	**No**	3	89.6	Yes
9	9	99.9	**No**	3	92.2	Yes
10	7	100	**No**	2	86.8	Yes
11	7	100	**Conditional**	4	79.2	Yes
12	7	100	**Conditional**	4	80	Yes
13	8	99.8	**Conditional**	4	81	Yes
14	8	100	**No**	3	96.3	Yes
15	9	99.9	**No**	2	78.5	Yes
16	14	80.7	Yes	3	84.9	Yes
17	15	77.9	**Conditional**	2	90.4	Yes
18	5	99.9	Yes	3	98.7	Yes
19	5	99.9	Yes	2	91.6	**No**
20	10	83.7	**No**	Note 1		
21	15	87.3	Yes			
22	15	88.2	Yes			
23	15	88.2	Yes			
24	11	83.2	**No**			
25	17	80.2	Yes			
26	16	81.5	Yes			
27	13	80.9	Yes			
28	15	76.8	Yes			
29	14	85.3	Yes			
30	14	99.2	Yes			

Note 1: The 11 loads not listed were identical to one of the loads presented. Since they provided no contribution, they were omitted.

[2] Chalk Number is the term used for the index of load plans and aircraft.

Chapter 5 - Future Research

This study has developed a methodology for solving the MMDKP using tabu search and has validated the packing heuristic. The best solutions were found using the *All/One* mixing strategy; however, the growth in computational time, as the fleet size increases, is a significant drawback. The development of a program that makes use of parallel processors could remedy this problem and allow the use of the *All/One* strategy on problems with larger fleet sizes.

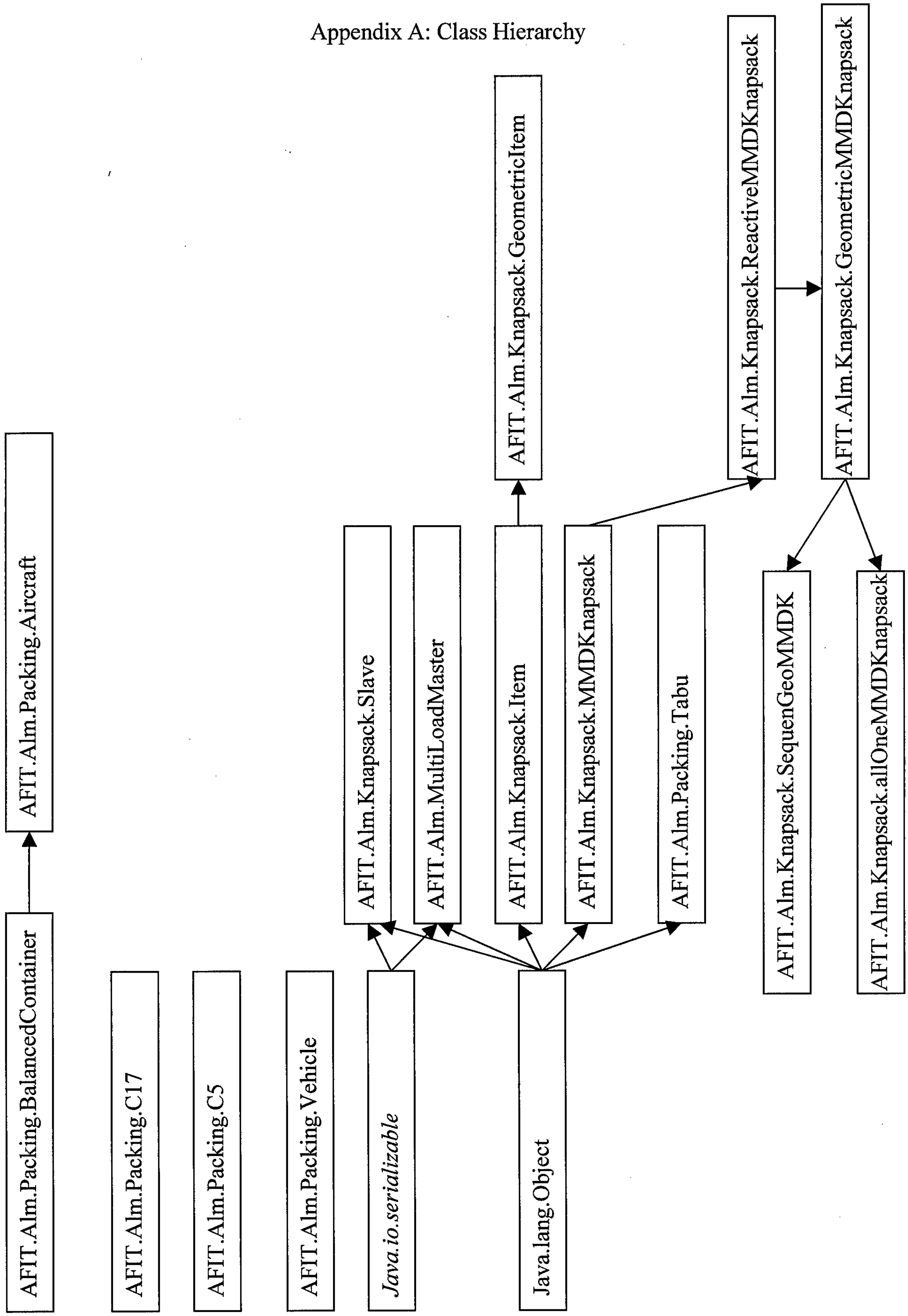
The development of a three-dimensional packing algorithm would make the model more realistic. The current heuristic prevents items from extending over the top of others. A three-dimensional model could also make the necessary allowances needed to simulate the 10-degree up angle of the ramp.

Extending the packing heuristic to provide a larger amount of information would encourage a higher quality solution as the number of aircraft increases. Additional information about the packing constraints will improve the quality of any decision made. Currently, items are prioritized using profit ratios that are adjusted by information generated by the packing heuristic. This information is only returned if a load is found to be unpackable. If the packing algorithm returned dimensions of unused sections of space, then items could be given preference in the selection process if their dimensions are similar to the available space.

Developing other strategies for combining the two heuristics could also extend this research. Methods that initialize only a portion of the fleet at a time were considered; however, they were never implemented. The problems considered by this study consisted

of at most five aircraft. Given this fleet size, any contribution these unused strategies would have made was deemed insignificant.

Appendix A: Class Hierarchy



The first step during this undertaking was a restructuring of Chocolaad's Knapsack heuristic; his packing heuristic was unchanged. This restructuring enabled the class hierarchy to shrink from a 16-page layout to the one page layout (A-1). This change simplified the code structure, so that each major portion was self-contained within an object. This object-oriented design used Chocolaad's work as a scaffolding. Once the redesign was complete the scaffolding was removed and a truer, less intimidating and more self-explanatory implementation was established.

The most obvious and necessary change made was a complete redesign of the data structures. Chocolaad makes extensive use of the OrderedList data structure. While this was a very practical, and in some sense efficient, structure for his application it was not usable within ours. If OrderedLists were maintained for the MMDKP, it would not be possible to identify the specific load plan the selected items had been placed on, only that they had been selected. This could lead to the possibility that an item will be off loaded from an aircraft that was not holding it. If such an event occurred it would credit an aircraft's constraints for an item that had not utilized them, while charging the actual aircraft's constraints for an item the solution value was not receiving credit for. This implementation used simple multidimensional arrays instead of the OrderedList. This change has the additional benefit of simplifying the maintenance and expansion of the code.

The class hierarchy (A-1) works in the following manner. MMDKnapsack solves the MMDKP, using standard critical event tabu. Reactive MMDKnapsack extends MMDKnapsack by inheriting from it and adding the necessary methods for reactive tabu, once again solving the MMDKP. GeometricMMDKnapsack inherits from the

ReactiveMMDKP object, and is the first to enforce the packing constraints. This object is the *All/All* implementation. SequentialGeoMMDK and allOneMMDKnapsack both inherit from GeometricMMDKnapsack and are the implementations for *Sequential* and *All/One*.

With only one exception the other objects within the hierarchy are used by the objects listed above. That one exception is MultiLoadMast, the overall controller of the solution process. BalancedContainer is used to define the object Aircraft, and by doing so enforces the balancing constraints once the packing is called. C17 and C5 are types of the object Aircraft, and model the aircraft for which they are named. Item and GeometricItem objects are used to define the cargo items. The main difference between the two is the object Vehicle that GeometricItem can call. The Vehicle object is used to pass the specifications of the selected items from the knapsack to the packing heuristic. GeometricMMDKnapsack, SequentialGeoMMDK, and allOneMMDKnapsack communicate with Tabu by calling the Slave object. The Tabu object is the packing heuristic.

Appendix B: Validation of Romaine/Chocolaad Algorithm

The following are the 19 distinct load plans that were generated using the algorithms developed by Romaine and Chocolaad. They were presented to SMSgt Patrick R. Farley, who conducted a detailed analysis of them and judged their operational feasibility. Below are the assumptions that he made and a summary of his findings (in his own words):

Assumptions

- No cargo exceeds 142" high
- Unless otherwise indicated all cargo is rolling stocks
- Axle limitations, psi [pounds pre square inch], plf [pounds per linear foot] are within cargo loading envelope
- Any item of cargo exceeding 65000Lb is loaded centerline
- If item is a tracked vehicle, no limitations for loading tracked vehicles are exceeded

Findings

- For side by side loading tolerances are close but attainable. Usually around 20″ of lateral space free, this would equate to roughly 10″ between items and 5″ between item and side envelope. Items loaded on right side would be limited to 138″ due to electrical wiring interference.
- When cargo is loaded on the ramp baggage for troops would have to be floor loaded vs using baggage pallet ok if < 25 troops.
- If an item is loaded on the ramp height is limited to ≤128″ due to incline
- All load plans allow for troops/gear/baggage depending on configuration (i.e. load side by side to allow for an open ramp)

- 1 load plan was rejected
- Plans not realistic in that troops/gear/baggage that would usually accompany a mission like this not included.

Each load plan will be presented in the following format:

Indexing number that corresponds to Table 2

Chalk #1

List of items packed:

Item #	Value	# Selected	Dimensions	weight
ID 283	Profit 107840	Selected 1	length 323 width 144	weight 107840

Summary of all equipment packed:

Total number of equipment packed 1

Loadmaster Comments: (In his own words)

None

Chalk # 2

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID 201 Profit	82270	Selected 1	length 405	width 113	weight 82270
ID 188 Profit	5480	Selected 1	length 254	width 91	weight 5480

Summary of all equipment packed

Total number of equipment packed 2

Loadmaster Comments:

-2 items loaded centerline @ 87,750

-159″ of floor & all ramp open

Chalk # 3

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID 411	Profit 7500	Selected 1	length 204	width 86	weight 7500
ID 201	Profit 82270	Selected 1	length 405	width 113	weight 82270

Summary of all equipment packed

Total number of equipment packed 2

Loadmaster Comments:

-2 items loaded centerline @ 89,770

-209″ of floor & all ramp open

Chalk # 4

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID 201	Profit 82270	Selected 1	length 405	width 113	weight 82270
ID 120	Profit 6813	Selected 1	length 165	width 95	weight 6813

Summary of all equipment packed

Total number of equipment packed 2

Loadmaster Comments:

-2 items loaded centerline @ 89,083

-248″ of floor & all ramp open

Chalk # 5

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID 252	Profit 33360	Selected 3	length 380	width 98	weight 33360

Summary of all equipment packed

Total number of equipment packed 3

Loadmaster Comments:

-2 items loaded side by side

-1 item loaded centerline @ 100,080

-Cargo ramp remains open

Chalk # 6

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID 606	Profit 21915	Selected 2	length 251	width 96	weight 21915
ID 427	Profit 31140	Selected 2	length 271	width 101	weight 31140

Summary of all equipment packed

Total number of equipment packed 4

Loadmaster Comments:

-4 items loaded centerline @ 106,110

-Last item loaded on ramp

or

-2 items may be loaded side by side with 2 items centerline

-Ramp would be free

or

-2 items side by side with 2 item side by side

-Ramp would be free

Chalk # 7

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID 455	Profit 31800	Selected 1	length 351	width 99	weight 31800
ID 113	Profit 65800	Selected 1	length 458	width 100	weight 65800

Summary of all equipment packed

Total number of equipment packed 2

Loadmaster Comments:

-2 items loaded centerline @ 97,600

-Ramp open

Chalk # 8

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID 544	Profit 32840	Selected 3	length 396	width 98	weight 32840

Summary of all equipment packed

Total number of equipment packed 3

Loadmaster Comments:

-2 items loaded side by side, one loaded centerline @ 98,520

-Ramp remains open

Chalk # 9

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID 605	Profit 33810	Selected 3	length 359	width 96	weight 33810

Summary of all equipment packed

Total number of equipment packed 3

Loadmaster Comments:

-2 items side by side, 1 item centerline @ 101,430

-Ramp remains open

Chalk # 10

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID 276	Profit 47723	Selected 2	length 397	width 113	weight 47723

Summary of all equipment packed

Total number of equipment packed 2

Loadmaster Comments:

-2 items loaded centerline @ 95,446

-Ramp remains open

Chalk # 11

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID 588	Profit 21534	Selected 2	length 275	width 96	weight 21534
ID 82	Profit 22000	Selected 2	length 465	width 96	weight 22000

Summary of all equipment packed

Total number of equipment packed 4

Loadmaster Comments:

-2 items side by side with 2 items side by side @ 87,068

-Ramp remains open

or

- 2 items side by side with 2 items centerline

-Last item on ramp slightly infringing on floor

Chalk # 12

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID 577	Profit 21750	Selected 1	length 352	width 96	weight 21750
ID 540	Profit 22070	Selected 3	length 311	width 97	weight 22070

Summary of all equipment packed

Total number of equipment packed 4

Loadmaster Comments:

-2 items side by side with 2 items side by side @ 87,960

-Ramp open

or

-2 items side by side with 2 items centerline

-Ramp is loaded

Chalk # 13

List of items packed

Item #	Value	# Selected	Dimensions		weight:
ID 541	Profit 22275	Selected 4	length 332	width 97	weight 22275

Summary of all equipment packed

Total number of equipment packed 4

Loadmaster Comments:

-2 items side by side with 2 items side by side @ 89,100

-Ramp open

or

-2 items side by side with 2 items centerline

-Last item loaded span ramp/floor

-Ramp loaded

Chalk # 14

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID 600	Profit 18259	Selected 2	length 254	width 96	weight 18259
ID 402	Profit 69460	Selected 1	length 312	width 141	weight 69460

Summary of all equipment packed

Total number of equipment packed 3

Loadmaster Comments:

-3 items loaded centerline @ 105978

-Will infringe slightly on ramp

-1/2 of ramp open

-item 420 must be loaded centerline

Chalk # 15

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID 445	Profit 43180	Selected 2	length 384	width 101	weight 43180

Summary of all equipment packed

Total number of equipment packed 2

Loadmaster Comments:

-2 items loaded centerline @ 86360

-Ramp is open

Chalk #16

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID 427	Profit 31140	Selected 3	length 271	width 101	weight 31140

Summary of all equipment packed

Total number of equipment packed 3

Loadmaster Comments:

-3 items loaded centerline @ 93420

-Ramp open

Chalk # 17

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID 417	Profit 49700	Selected 2	length 431	width 96	weight 49700

Summary of all equipment packed

Total number of equipment packed 2

Loadmaster Comments:

-2 items loaded ok @99400

-Ramp open

Chalk # 18

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID605	Profit 33810	Selected 2	length 359	width 96	weight 33810
ID 604	Profit 41000	Selected 1	length 358	width 102	weight 41000

Summary of all equipment packed

Total number of equipment packed 3

Loadmaster Comments:

-2 items side by side with 1 ok @ 108620

-Ramp open

Chalk # 19

List of items packed:

Item #	Value	# Selected	Dimensions		weight
ID 591	Profit 50400	Selected 2	length 622	width 144	weight 50400

Summary of all equipment packed

Total number of equipment packed 2

Loadmaster Comments:

CAN NOT BE LOADED

-Only 1 item can be loaded ok on C-17.

--Limiting factor is longitudinal space. Item is too wide for side by side loading.

Appendix C: Validation of Win ALM

The following are the 30 load plans that were generated using Win ALM. They were presented to SMSgt Patrick R. Farley who conducted a detailed analysis of them and judged their operational feasibility. Below are the assumptions that he made and a summary of his findings, in his own words.

Assumption:

- Any item exceeding 65,000lb will be loaded centerline.
- Minimal space between items ≥ 15″
  - Lateral spacing may be 0
- All items are rolling stock and must be placed in fwd/aft direction.
- Items are not stacked on each other.

Findings:

- Chalks 1,2,3 restraints difficult to achieve. (Possible)
  - Reoccurring problem with load plan programs. Does not account for space needed for tie downs.
  - Plan for 15″-20″ longitudinal space between items
- Chalks 4,5,6,7,8,9,10 cannot be loaded as configured. It appears that the program does not take into account the fact that on C-17 any item ≥ 65,000lb must be loaded centerline.
- Chalks 11,12,13 are theoretically possible. However, again longitudinal space is almost nonexistent. It can be done as long as restraints can be achieved.
- Chalk 14,15 can not be loaded. The heavy item must be loaded centerline there by reducing space.
- Chalk 20 not realistic. To provide space for ramp to come up all items must literally touch.

Each aircraft's load plan will have the following elements:

Indexing Chalk Number:	Validation: result
Chalk No.: #	Validation: Result (Pass, Fail, or Theoretically)
Aircraft Type: C17	

Load Summery:

% Space Used:	82.75
% Weight Used:	82.08
Payload:	# of Lbs. of Equipment Packed
Qty Pax:	# of Personnel carried Pax
Qty Equip:	# of Cargo Items Packed

This information had no impact on this work but was retained for the authenticity of the ALM load plans.

Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	4922
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
#	α#####P##	#Lbs.	# Lbs.	#″	#″	#″
#	α#####P##	#Lbs.	# Lbs.	#″	#″	#″
#	α#####P##	#Lbs.	# Lbs.	#″	#″	#″
#	α#####P##	#Lbs.	# Lbs.	#″	#″	#″

Gr Wt	Grows Weight (pounds)
Tar Tar	Tear Weight (pounds)
Len	Length (inches)
Wid	Width (inches)
Hei	Height (inches)

Chalk No.: 1
Aircraft Type: C17

Validation: Conditional

Load Summery:

% Space Used:	82.75
% Weight Used:	82.08
Payload:	90287
Qty Pax:	4
Qty Equip:	8
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	4922
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	S70517P01*	16285	16295	416	115	72
1	Z94492P01*	21915	21915	251	96	145
1	T59414P05*	9350	9350	221	87	105
2	X40146P02	16031	13570	279	96	81
1	G95535P01	3750	3750	243	39	43
1	V48441P02	605	605	133	29	26
1	L76762P02	5360	5360	148	74	84

Chalk No.: 2 Validation: Conditional
Aircraft Type: C17

Load Summery:

% Space Used:	82.75
% Weight Used:	82.08
Payload:	90287
Qty Pax:	4
Qty Equip:	8
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	4922
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	S70517P01*	16285	16295	416	115	72
1	Z94492P01*	21915	21915	251	96	145
1	T59414P05*	9350	9350	221	87	105
2	X40146P02	16031	13570	279	96	81
1	G95535P01	3750	3750	243	39	43
1	V48441P02	605	605	133	29	26
1	L76762P02	5360	5360	148	74	84

Chalk No.: 3 Validation: Conditional
Aircraft Type: C17

Load Summery:

% Space Used:	83.52
% Weight Used:	82.34
Payload:	90571
Qty Pax:	4
Paty Equip:	9
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	4922
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	S70517P01*	16285	16285	416	115	72
1	Z94492P01*	21915	21915	251	96	145
1	T59414P05*	9350	9350	221	87	105
2	X40146P02	16031	13570	279	96	81
1	G95535P01	3750	3750	243	39	43
1	V48441P03	615	615	188	21	21
1	L76762P02	5360	5360	148	74	84
1	V48441P04	274	274	134	12	25

Chalk No.: 4 Validation: Fail
Aircraft Type: C17

Load Summery:

% Space Used:	82.50
% Weight Used:	87.33
Payload:	96064
Qty Pax:	4
Qty Equip:	9
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	0
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	L46979P02*	82270	82270	405	113	137
1	R11154P03	5100	5100	431	104	44
2	S25690P01*	430	430	147	91	113
2	E02807P01	2445	2445	169	94	41
2	K39774P01	855	855	151	70	67
1	V48441P04	274	274	134	12	25

Chalk No.: 5 Validation: Fail
Aircraft Type: C17

Load Summery:

% Space Used:	84.15
% Weight Used:	90.99
Payload:	100094
Qty Pax:	4
Qty Equip:	9
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	0
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	L46979P02*	82270	82270	405	113	137
1	R11154P03	5100	5100	431	104	44
4	E02807P01	2445	2445	169	94	41
2	K39774P01	855	855	151	70	67
1	V48441P04	274	274	134	12	25

Chalk No.: 6 Validation: Fail
Aircraft Type: C17

Load Summery:

% Space Used:	84.81
% Weight Used:	94.43
Payload:	103877
Qty Pax:	3
Qty Equip:	8
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	1987
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	L46979P02*	82270	82270	405	113	137
1	R11154P03	5100	5100	431	104	44
4	E02807P01	2445	2445	169	94	41
1	W95811P02	3793	2670	166	83	55
1	W95537P02	2214	1350	147	74	50

Chalk No.: 7 Validation: Fail
Aircraft Type: C17

Load Summery:

% Space Used:	84.73
% Weight Used:	97.13
Payload:	106847
Qty Pax:	3
Qty Equip:	9
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	4233
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	L46979P02*	82270	82270	405	113	137
1	R11154P03	5100	5100	431	104	44
2	E02807P01	2445	2445	169	94	41
3	W95811P02	3793	2670	166	83	55
1	W95537P02	2214	1350	147	74	50
1	V48441P04	274	274	134	12	25

Chalk No.: 8 Validation: Fail
Aircraft Type: C17

Load Summery:

% Space Used:	83.71
% Weight Used:	99.58
Payload:	109543
Qty Pax:	3
Qty Equip:	9
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	6479
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	L46979P02*	82270	82270	405	113	137
1	R11154P03	5100	5100	431	104	44
5	W95811P02	3793	2670	166	83	55
1	W95537P02	2214	1350	147	74	50
1	V48441P04	274	274	134	12	25

Chalk No.: 9 Validation: Fail
Aircraft Type: C17

Load Summery:

% Space Used:	84.55
% Weight Used:	99.99
Payload:	109986
Qty Pax:	1
Qty Equip:	9
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	2246
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	L46979P02*	82270	8227	405	113	137
2	T61973P02	4300	4300	216	96	39
2	R09696P02	4300	4300	216	96	39
2	W95811P02	3793	2670	166	83	55
1	T16597P01	2290	2290	146	88	84
1	Q16048P03	400	400	116	48	52

Chalk No.: 10 Validation: Fail
Aircraft Type: C17

Load Summery:

% Space Used:	78.52
% Weight Used:	100.00
Payload:	110000
Qty Pax:	0
Qty Equip:	7
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	1790
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	L46979P02*	82270	82270	405	113	137
4	K28601P01	5480	5480	254	91	93
1	W95811P02	3793	2670	166	83	55
1	W95537P02	2214	1350	147	74	50

Chalk No.: 11 Validation: Conditional
Aircraft Type: C17

Load Summery:

% Space Used:	74.98
% Weight Used:	100.00
Payload:	110000
Qty Pax:	0
Qty Equip:	7
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	3005
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	L46979P02*	82270	82270	405	113	137
2	S75038P01*	7180	7180	276	96	129
1	E02533P01	3675	3675	188	98	47
2	W95811P02	3793	2670	166	83	55
1	W95537P02	2214	1350	147	74	50

Chalk No.: 12 Validation: Conditional
Aircraft Type: C17

Load Summery:

% Space Used:	74.98
% Weight Used:	100.00
Payload:	110000
Qty Pax:	0
Qty Equip:	7
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	3005
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	L46979P02*	82270	82270	405	113	137
2	S75038P01*	7180	7180	276	96	129
1	E02533P01	3675	3675	188	98	47
2	W95811P02	3793	2670	166	83	55
1	W95537P02	2214	1350	147	74	50

Chalk No.: 13	Validation: Conditional
Aircraft Type: C17	

Load Summery:

% Space Used:	76.75
% Weight Used:	99.86
Payload:	109847
Qty Pax:	0
Qty Equip:	8
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	1728
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	L46979P02*	82270	82270	405	113	137
2	S75038P01*	7180	7180	276	96	129
1	E02533P01	3675	3675	188	98	47
1	C66602P01	4840	4840	192	94	94
2	W95537P02	2214	1350	147	74	50
1	V48441P04	274	274	134	12	25

Chalk No.: 14 Validation: Fail
Aircraft Type: C17

Load Summery:

% Space Used:	80.35
% Weight Used:	100.00
Payload:	110000
Qty Pax:	0
Qty Equip:	8
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	835
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	L46979P02*	82270	82270	405	113	137
3	E02533P01	3675	3675	188	98	47
3	C66602P01	4840	4840	192	94	94
1	W95537P02	2214	1350	147	74	50

Chalk No.: 15 Validation: Fail
Aircraft Type: C17

Load Summery:

% Space Used:	83.14
% Weight Used:	99.94
Payload:	109933
Qty Pax:	1
Qty Equip:	9
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	1728
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	L46979P02*	82270	82270	405	113	137
3	E02533P01	3675	3675	188	98	47
2	C66602P01	4840	4840	192	94	94
1	T16597P01	2290	2290	146	88	84
2	W95537P02	2214	1350	147	74	50

Chalk No.: 16 Validation: Pass
Aircraft Type: C17

Load Summery:

% Space Used:	84.84
% Weight Used:	80.67
Payload:	88739
Qty Pax:	5
Qty Equip:	14
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	1123
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	Z65946P01*	50400	50400	622	144	114
1	W95811P02	3793	2670	166	83	55
1	Q23623P01	600	600	148	92	88
1	X17831P09	5390	5390	122	86	75
2	J04717P20	4000	4000	151	52	56
2	J37890P04	5180	5180	117	45	69
5	V48441P04	274	274	134	12	25
1	X17831P10	2226	2226	93	93	40

Chalk No.: 17 Validation: Conditional
Aircraft Type: C17

Load Summery:

% Space Used:	81.52
% Weight Used:	77.88
Payload:	85671
Qty Pax:	5
Qty Equip:	15
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	1123
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	Z65946P01*	50400	50400	622	144	114
1	W95811P02	3793	2670	166	83	55
1	Q23623P01	6000	6000	148	92	88
3	J04717P20	4000	4000	151	52	56
2	J37890P04	5180	5180	117	45	69
7	V48441P04	274	274	134	12	25

Chalk No.: 18 Validation: Pass
Aircraft Type: C17

Load Summery:

% Space Used:	35.44
% Weight Used:	99.91
Payload:	109900
Qty Pax:	0
Qty Equip:	5
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	0
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	R50681P04*	107840	107840	323	144	124
2	K39774P01	855	855	151	70	67
2	F07520P02	175	175	121	21	5

Chalk No.: 19 Validation: Pass
Aircraft Type: C17

Load Summery:

% Space Used:	35.44
% Weight Used:	99.91
Payload:	109900
Qty Pax:	0
Qty Equip:	5
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	0
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	R50681P04*	107840	107840	323	144	124
2	K39774P01	855	855	151	70	67
2	F07520P02	175	175	121	21	5

Chalk No.: 20 Validation: Fail
Aircraft Type: C17

Load Summery:

% Space Used:	86.43
% Weight Used:	83.74
Payload:	92112
Qty Pax:	1
Qty Equip:	10
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	0
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	T48941P02*	69460	69460	312	141	123
1	R11154P03	5100	5100	431	104	44
2	T48941P08	3800	3800	240	96	30
2	E02807P01	2445	2445	169	94	41
1	J04717P20	4000	4000	151	52	56
3	V48441P04	274	274	134	12	25

Chalk No.: 21 Validation: Pass
Aircraft Type: C17

Load Summery:

% Space Used:	87.60
% Weight Used:	87.32
Payload:	96049
Qty Pax:	0
Qty Equip:	15
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	0
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	T48941P02*	69460	69460	312	141	123
1	R11154P03	5100	5100	431	104	44
2	T48941P08	3800	3800	240	96	30
2	K39774P01	855	855	151	70	67
1	F07520P02	175	175	121	21	5
6	V48441P04	274	274	134	12	25
2	J37890P04	5180	5180	117	45	69

Chalk No.: 22 Validation: Pass
Aircraft Type: C17

Load Summery:

% Space Used:	88.44
% Weight Used:	88.15
Payload:	96969
Qty Pax:	2
Qty Equip:	15
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	0
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	T48941P02*	69460	69460	312	141	123
1	R11154P03	5100	5100	431	104	44
2	T48941P08	3800	3800	240	96	30
2	K39774P01	855	855	151	70	67
1	V48441P03	615	615	188	21	21
6	V48441P04	274	274	134	12	25
2	J37890P04	5180	5180	117	45	69

Chalk No.: 23 Validation: Pass
Aircraft Type: C17

Load Summery:

% Space Used:	88.44
% Weight Used:	88.15
Payload:	96969
Qty Pax:	2
Qty Equip:	15
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	0
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	T48941P02*	69460	69460	312	141	123
1	R11154P03	5100	5100	431	104	44
2	T48941P08	3800	3800	240	96	30
2	K39774P01	855	855	151	70	67
1	V48441P03	615	615	188	21	21
6	V48441P04	274	274	134	12	25
2	J37890P04	5180	5180	117	45	69

Chalk No.: 24 Validation: Fail
Aircraft Type: C17

Load Summery:

% Space Used:	85.28
% Weight Used:	83.22
Payload:	91546
Qty Pax:	0
Qty Equip:	11
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	0
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	1
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	4600
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	P27821P01*	60050	690050	512	119	130
1	R11154P03	5100	5100	431	104	44
2	K39774P01	855	855	151	70	67
3	V48441P04	274	274	134	12	25
2	J04717P20	400	400	151	52	56
1	J37890P04	5180	5180	117	45	69
1	X17831P07	5730	5730	147	87	83

Chalk No.: 25 Validation: Pass
Aircraft Type: C17

Load Summery:

% Space Used:	83.32
% Weight Used:	80.24
Payload:	88266
Qty Pax:	0
Qty Equip:	17
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	0
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	P27821P01*	60050	60050	512	119	130
1	R11154P03	5100	5100	431	104	44
2	K39774P01	855	855	151	70	67
9	V48441P04	274	274	134	12	25
3	J37890P04	5180	5180	117	45	69
1	J04717P19	3400	3400	144	60	57

Chalk No.: 26 Validation: Pass
Aircraft Type: C17

Load Summery:

% Space Used:	83.57
% Weight Used:	81.47
Payload:	89612
Qty Pax:	0
Qty Equip:	16
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	0
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	P27821P01*	60050	60050	512	119	130
1	R11154P03	5100	5100	431	104	44
2	K39774P01	855	855	151	70	67
8	V48441P04	274	274	134	12	25
2	J37890P04	5180	5180	117	45	69
1	J04717P19	3400	3400	144	60	57
1	W89557P11	6800	6800	122	67	58

Chalk No.: 27 Validation: Pass
Aircraft Type: C17

Load Summery:

% Space Used:	80.44
% Weight Used:	80.87
Payload:	88958
Qty Pax:	10
Qty Equip:	13
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	3022
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	S70517P01*	16285	16285	416	115	72
1	T61103P04*	21600	21600	271	96	115
1	X40077P02	16548	13526	265	98	82
1	X17831P08	4380	4380	147	87	83
5	V48441P04	274	274	134	12	25
1	W89557P11	6800	6800	122	67	58
2	T49255P02	9700	9700	166	79	78
1	F07520P02	175	175	121	21	5

Chalk No.: 28 Validation: Pass
Aircraft Type: C17

Load Summery:

% Space Used:	81.79
% Weight Used:	76.84
Payload:	84527
Qty Pax:	4
Qty Equip:	15
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	3022
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	S70517P01*	16285	16285	416	115	72
1	T61103P04*	21600	21600	271	96	115
1	X40077P02	16548	13526	265	98	82
1	X17831P08	4380	4380	147	87	83
6	V48441P04	274	274	134	12	25
2	T49255P02	9700	9700	166	79	78
2	F07520P02	175	175	121	21	5
1	J04717P19	3400	3400	144	60	57

Chalk No.: 29 Validation: Pass
Aircraft Type: C17

Load Summery:

% Space Used:	81.73
% Weight Used:	85.25
Payload:	93772
Qty Pax:	4
Qty Equip:	14
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	3022
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	S70517P01*	16285	16285	416	115	72
1	T61103P04*	21600	21600	271	96	115
1	X40077P02	16548	13526	265	98	82
1	X17831P08	4380	4380	147	87	83
6	V48441P04	274	274	134	12	25
2	T49255P02	9700	9700	166	79	78
1	J04717P19	3400	3400	144	60	57
1	J40150P01	9495	9495	144	50	75

Chalk No.: 30 Validation: Pass
Aircraft Type: C17

Load Summery:

% Space Used:	91.55
% Weight Used:	90.18
Payload:	99194
Qty Pax:	13
Qty Equip:	14
Lbs. Acc. Sup. on Equip:	0
Lbs. NMUE on Equip:	0
Qty. Pallets for Acc. Sup.:	0
Qty. Pallets for Ammunition:	0
Qty. Pallets for NMUE pal:	0
Qty. Pallets for NMUE pal or eqp:	0
Lbs. Acc. Sup. on Pallets:	0
Lbs. Ammunition on Pallets:	0
Lbs. NMUE(pal only) on Pallets:	0
Lbs. NMUE(pal or eqp) on Pallets:	0

Equipment List:

Equipment:	Id	Gr Wt	Tar Wt	Len	Wid	Hei
1	T60353P07*	16360	16360	193	104	112
1	K28601P01	5480	5480	254	91	93
1	X58367P10	14200	14200	264	96	98
1	S74490P02*	15890	15980	320	97	134
2	F55289P01	13400	13400	240	96	96
6	V48441P04	274	374	134	12	25
1	T49255P02	9700	9700	166	79	78
1	Q23623P01	6000	6000	148	92	88

Appendix D: Example of Selection Process

This is a simple example of a two aircraft system. The item to be packed next has already been selected; the decision being made is which aircraft should the item be loaded on. Figure 15 depicts the aircraft constraints as bars, with the percentage of capacity already consumed. The first two sets of bars represent the resources consumed by the current load plan. The new item can be added to either aircraft; however if placed on aircraft two, it will consume almost all of the remaining volume, but leave 50% of the original weight capacity unused. Placing it on aircraft one, on the other hand, will require 40% of the unused weight capacity and 53% of the volume. While the remaining space can be occupied by smaller items on aircraft one, this is unlikely on aircraft two. A real life example of this would be placing an item such as toilet paper (requiring lots of volume but very little weight) on the same load plan as uranium depleted shells (requiring lots of weight and very little volume.)

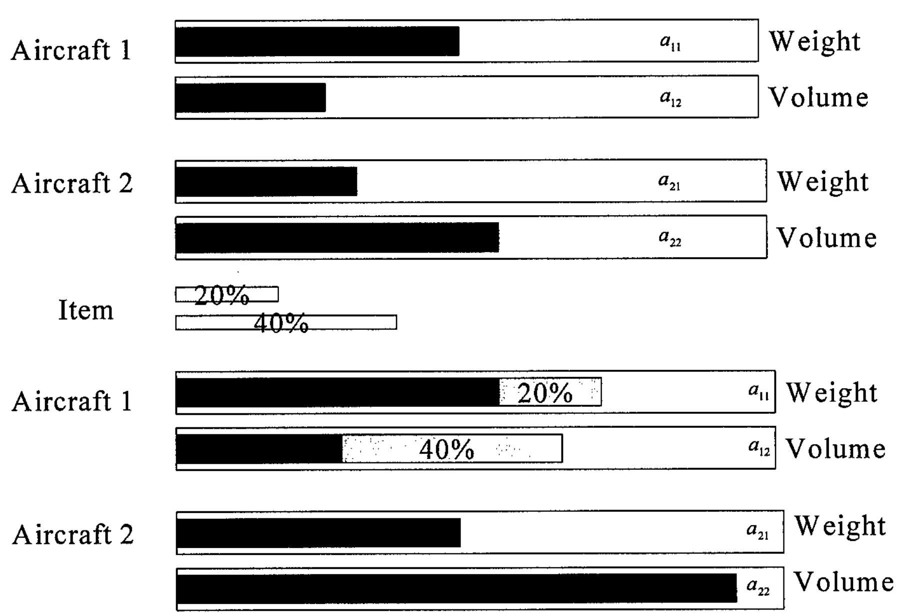


Figure 15. Constraint Utilization

Bibliography

[1] Aarts, E. and J. k. Lenstra. *Local Search in Combinatorial Optimization.* Chichester: Wiley-Intescience Publication, (1997).

[2] Anderson, V., M. Baldwin, J. Fecteau, and S. McBride. AFSC Pub 1, The joint staff Officer's Guide 1993, reprinted in *Joint Warfare Studies*: Air University USAF, Maxwell AFB, Alabama (1996).

[3] Ahrens, J. H. and G. Finke. "Merging and Sorting Applied to the Zero-One Knapsack Problem," *Operations Research*, 23(6): 1099-1109 (1975).

[4] Amiouny, S. V., J. Bartholdi, and J. V. Vate. "Balanced Loading," *Operations Research*, 40(2):238-245 (1992).

[5] Battiti, R.. "Reactive Search: Toward Self-Tuning Heuristics." *Modern Heuristic Search Methods* edited by V. J. Rayward-Smith, I.H. Osman, C. R. Reeves and G. D. Smith, 61-83, John Wiley and Sons Ltd, (1996).

[6] Battiti, R. and G. Tecchiolli. "The Reactive Tabu Search," *ORSA Journal on Computing*, 6(2);126-140 (1992).

[7] Blazewicz, J., P. Hawryluk and R. Walkowiak. "Using a Tabu Search Approach for Solving the Two-Dimensional Irregular Cutting Problem," *Annals of Operations Research*, 41: 313-325 (1993).

[8] Brosh, I. "Optimal Cargo Allocation on Board a Plane: A Sequential Linear Programming Approach," *European Journal of Operational Research*, 8:40-46 (1981).

[9] Chocolaad, C. A. *Solving Geometric Knapsack Problems using Tabu Search Heuristics*. MS Thesis, Air Force Institute of Technology, WPAFB, OH. (1998).

[10] Coffman, E. G., M. R. Garey, D. S. Johnson. "Approximation algorithms for Bin-Packing – An Updated Survey." *Algorithm Design for Computer System Design* edited by G. Ausiello, 46-106, New york: Springer-Verlag, 1984.

[11] Cochard, D. D. and K. A. Yost. "Improving Utilization of Air force Cargo Aircraft," *Interfaces*, 15:53-68 (1985).

[12] Cormen, T. H., C. E. Leiserson, and R. L. Rivest. *Introduction to Algorithms*. Cambridge, Massachusetts: The MIT Press (1990).

[13] Decker, R., and S. Hirshfield. *Working Classes, Data structures and algorithms using C++*. Boston: PWS Publishing Company (1996).

[14] Dowsland, K. A. and W. B Dowsland. "Packing Problems," *European Journal of Operational Research*, 56:2-14 (1992).

[15] Dowsland, K. A. "Simple Tabu Thresholding and the Pallet Loading Problem." *Meta-Heuristics Theory and Applications* edited by I. H. Osman and James P. Kelly, 381-405, Kluwer Academic Publishers (1996).

[16] Dowsland, K. A. "Some Experiments with Simulated Annealing Techniques for Packing Problems," *European Journal of Operational Research*, 68: 389-399 (1993).

[17] Dyckhoff, Harald. "A Typology of Cutting and Packing Problems," *European Journal of Operational Research*, 44:145-159 (1990).

[18] Eilon, S. and N. Christofides. "The Loading Problem," *Management Science*, 17(5): 259-269 (J1971).

[19] Fox, G. E. and C. J. Nachtsheim.. "An Analysis of Six Greedy Selection Rules on a Class of Zero-One Integer Programing Models," *Naval Research Logistics*, 37: 299-307 (1990).

[20] Geary, David M. and Alan L. McClellan. *Graphic Java, Mastering the AWT*. Mountain View: Sunsoft Press (1997).

[21] Gilmore, P.C. and R. E. Gomory. "The Theory and Computation of Knapsack Functions," *Operations Research*, 14: 1045-1074 (1966).

[22] Glover, F. and M. Laguna. *Tabu Search*. Boston: Kluwer Academic Publishers (1997).

[23] Glover, F.. "Tabu Search: A Tutorial," *Interfaces*, 20(4):74-94 (1990).

[24] Glover, F.. "Tabu Search -Part I," *ORSA Journal on Computing* 1(3): 190-206 (1989).

[25] Glover, F. "Tabu Thresholding: Improving Search by Nonmonotonic Trajectories," *ORSA Journal on Computing*, 7(4):416-442 (1995).

[26] Glover, F. and G. A. Kochenberger. "Critical Event Tabu Search for Multidemensional Knapsack Problems." *Meta – Heuristics Theory and Applications* edited by I. H. O. and James P. Kelly, 407-427, Kluwer Academic Publishers (1996).

[27] Heidelberg, K. R., G. Parnell, and J. Ames. "Automated Air Load Planning," *Naval Research Logistics,* 45(8):751-768 (1998).

[28] Huebner, W. F. "Load Planning, Rapid Mobilization and the Computer," *Air Force Journal of Logistics*, 6(1):22-24 (1982).

[29] Ingargiola, G. and J. F. Korsh. "An Algorithm for the Solution of the 0-1 Loading Problems," *Operations Research,* 23(6): 1110-1119 (1975).

[30] Jackson, J. R. and A. L. McClellan. *Java by Example*. Mountain View: Sunsorft Press (1996).

[31] Khuri, S., T.Bäck, and J. Heitkõtter. "The Zero/One Knapsack Problme and Genetic Algorithms". *Proceeding ACM Symposium of Applied Computation*, SAC '94.

[32] Kozen, D. *The Design and Analysis of Algorithms*. New York: Springer-Verlang (1992).

[33] Kucera, L. *Combinatorial Algorithms*. Bristol: Adam Hilger (1990).

[34] Larsen, O. and G. Mikkelsen. "An Interactive System for the Loading of Cargo Aircraft," *European Journal of Operational Research*, 4:367-373 (1980).

[35] Martello, S. and P. Toth. *Knapsack Problems: Algorithms and Computer Implementations*. New York: John Wiley and Sons, (1990).

[36] NG, K. Y.K. "A Multicriteria Optimization Approach To Aircraft Loading," *Operations Research*, 40(6): 1200-1205 (1992).

[37] Okada, S. and M. Gen "Optimization of system reliability Using 0-1 knapsack Problem with GUB structures," *Electronics and Communications in Japan, Part 3*, 77(9): 22-31 (1994).

[38] Rosenthal, R., S. Bakeret, L. Weng, D. Fuller, D. Goggins, A. Toy, and Y. Turker. "Application and Extension of the Thruput II Optimization Model for Airlift Mobility," *Military Operations Research*, 3(2):55-74 (1997).

[39] Szykman, S. and J. Cagan. "A Simulated Annealing Approach to Three Dimensional Component Packing," *ASME: Journal of Mechanical Design,* 117:308-314(1995).

[40] Theodoratos, V. E. and J. L. Grimsley. "The Optimal Packing of Arbitrarily-Shaped Polygons Using Simulated Annealing and Polynomial-Time Cooling

Schedules," *Computer Methods in Applied Mechanics and Engineering*, 125:53-70 (1995).

[41] Van der Linden, P. *Just Java and Beyond.* Palo Alto: Sunsoft Press, (1998).

[42] Yamada, T. and M. Futakawa. "Heuristics and reductions for the knapsack sharing problem," *Computers and Operations Research*, 24 (10): 961-967 (1997).

[43] Yost, K. and R. W. Hare. Airlift Estimation for MAC Cargo Aircraft. AFLMC-LY870104 AD-B125 174, Gunter AFB, AL 36114: Air Force Logistics Management Center, (1988).

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Research Impact Statement

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Related Thesis
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Title: Solving the Multidimensional Multiple Knapsack Problem with Packing Constraints Using Tabu Search

Subject: Air Lift Loading Problem

Air Force Program Description:
The use of computer generated airlift load plans to efficiently allocate aircraft resources during a deployment is of prime interest to the Air Force. Large amounts of cargo must be moved in an efficient manner, and due to the large scale of operations even a small percentage increase in efficiency can result in millions of dollars in savings. The current deployment-level model, Win ALM, has been developed significantly in the last decade, but still has serious flaws. A new way of solving this problem is to use a meta-heuristic approach, with the end goal of increasing efficiency in an operationally feasible period of time.

Impact Statement:
We establish that Win ALM has several flaws, particularly in the operational feasibility of the loads produced. The use of a meta-heuristic, in particular tabu search, produces operationally feasible results with more consistency than Win ALM, and does so in an operationally reasonable time. The use of tabu search to solve the multidimensional multiple knapsack represents an expansion of the field of implementation for the heuristic, validating its ability to solve large problems with relative ease.

Technical Abstract:
This thesis presents a methodology for solving the military aircraft load-scheduling problems modeled as a multidimensional multiple knapsack problem with packing constraints. Because of the computational time associated with applying conventional algorithms to this class of problem, we employ the tabu search heuristic to determine how much cargo a heterogeneous group of aircraft can carry. This study extends the previous work of Chocolaad in two areas. First, we modify Chocolaad's algorithms to solve the multiple knapsack problem under the constraints he defined for the Airlift Loading Problem. Second, we drop his assumption of a homogeneous group of aircraft. We validate our model by confirming its solutions with cargo loadmasters, and comparing the performance of our algorithm with the benchmark ALM.

Subject Terms: Knapsack, Tabu Search, Heuristics, Packing, Air Lift Loading

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This paper presents a methodology for solving military aircraft load-scheduling problems modeled as a multidimensional multple knapsack problem. Because of the computational time associated with applying conventional algorithms to this type of problem, we employ tabu search to determine how much cargo a heterogeneous group of aircraft can carry. This study extends the previous work of Chocolaad in two areas. First, we modify Chocolaad's algorithms to solve the multiple (rather than the single) knapsack problem under the constraints he defined for the Airlift Loading Problem. Second, we drop his assumption of a homogeneous group of aircraft. We validate our model by confirming its solutions with cargo loadmasters, and comparing the performance of our algorithm with the benchmark ALM.

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